

Numerical simulation of an inductively coupled discharge using an Eulerian Vlasov code

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RF inductive discharges are widely used for the state of the art plasma etching which is at the core of a revolutionary electronics technology in microprocessor fabrication and in other related material processing applications, whose theme is the design of matter on a molecular scale. In the present work, we present the first self-consistent simulation of such a discharge using a kinetic Eulerian Vlasov code to follow the fully nonlinear electron and ion dynamics. The electrostatic potential is calculated self-consistently on the wave time-scale, together with the associated longitudinal electric field and current at the second harmonic of the applied RF field. The generated second harmonic currents are more pronounced at lower frequency, in qualitative agreement with experimental observation.

The code is one-dimensional (1D) in x and applies a method of fractional steps for the solution of the Vlasov-Maxwell kinetic equations [1]. A RF coil excites an inductive electromagnetic field at the $x = 0$ boundary. The electrons are reflected at $x = 0$ to model the presence of an electrostatic sheath potential, and the ions are also reflected to preserve neutrality. This electromagnetic field which penetrates the plasma has the components $\vec{E} = E_y(x, t) \vec{e}_y$, $\vec{B} = B_z(x, t) \vec{e}_z$. E_y and B_z are related

by Faraday's law $\frac{\partial E_y}{\partial x} = -\frac{1}{c} \frac{\partial B_z}{\partial t}$.

The kinetic equation for the electrons and singly ionized ions is the one-dimensional Vlasov equation:

$$\frac{\partial f_e}{\partial t} + v_x \frac{\partial f_e}{\partial x} \pm \frac{e}{m_{e,i}} \left(E_x + \frac{u_{ye,i}}{c} B_z \right) \frac{\partial f_e}{\partial v_x} = 0 \quad (1)$$

There is no y dependence. The canonical momentum: $P_{ye,i} = m_{e,i} v_y \pm \frac{e}{c} A_y$ is conserved. We assume that the plasma is cold in the transverse direction y . In view of the conservation of the canonical momentum, $P_{ye,i}$ can be chosen initially to be zero. Then the y velocity components of electrons and ions obey their respective fluid equations.

$$\frac{\partial u_{ye,i}}{\partial t} = \mp \frac{e}{m_{e,i}} E_y \quad (2)$$

Maxwell's equations are written in terms of $F^\pm = E_y \pm B_z / c$

$$\left(\frac{\partial}{\partial t} \pm c \frac{\partial}{\partial x} \right) F^\pm = 4\pi e (n_e u_{ye} - n_i u_{yi}) \quad (3)$$

and the time step $\Delta t = \Delta x / c$ is chosen so that these fields are shifted one cell per time step without any interpolation [1]. Equation (1) is advanced in time using a fractional step or splitting technique, associated with cubic spline interpolation [1] and E_x is calculated from Poisson's equation:

$$\frac{\partial^2 \varphi}{\partial x^2} = -4\pi e (n_i - n_e); \quad E_x = -\frac{\partial \varphi}{\partial x} \quad \text{with } n_{i,e} = \int_{-\infty}^{\infty} f_{i,e}(x, v_x) dv_x \quad (4)$$

We note that the longitudinal electrostatic field E_x , whose calculation is so important [2], and which is often neglected in particle-in-cell code simulations of discharge plasmas [3], possibly due to statistical noise problems, is calculated here self-consistently using the accurate scheme presented in Ref. [4] and previously used in Ref. [1]. The simulation parameters which we choose are typical of inductively coupled discharge plasmas [3] (argon, with $T_e = 5 \text{ eV}$, $n_e = 10^{12} \text{ cm}^{-3}$, $\frac{\omega}{2\pi} = 13.56 \text{ MHz}$.)

Simulations were also done with argon with a lower frequency $f/2$. At $x=0$, a RF field $F^\pm = 2E_o \sin \omega_o t$ (with $E_o \approx 4 \text{ V/cm}$) is applied, and penetrates the plasmas. For the present model and parameters, the decay of the electromagnetic field very closely follows the usual law for the ordinary skin effect, $\exp(-x/\delta_s)$, with the scale length equal to the usual skin depth $\delta_s = c/\omega_{pe}$.

Figures 1-2 show the space-time profiles during one wave period of the transverse electric field E_y ,

the induced magnetic field B_z . In Fig.(3) we present the total acceleration term $E_x + u_{ye}B_z$ near the edge. The density is presented in Fig. (4). In Fig. (5) the total current, $J_x = J_{ex} + J_{ix}$ is presented. It is seen that the ion current nearly cancels the electronic current, and that the assumption [2] that the ion current does not respond to the field at the harmonic frequency is false for the specific case which we have considered here. Similarly, the net charge $(n_i - n_e)/n_o$, is quite small but finite, 2×10^{-4} . An interesting observation presented in [5] is that the currents at the second harmonic are more pronounced at lower frequency. We repeated the previous simulation using a RF frequency half the one previously used (6.78 MHz), and kept the same peak value of the RF electric field. All other parameters remained unchanged, including the incident electric field amplitude of approximately 4V/cm. The longitudinal electric field E_x and the total acceleration term $E_x + u_{ye}B_z$ have a peak about 4 times higher compared to the previous case. The peak of the total current density J_x , presented in Fig. (6) has approximately doubled with respect to what is shown in Fig. (5).

References

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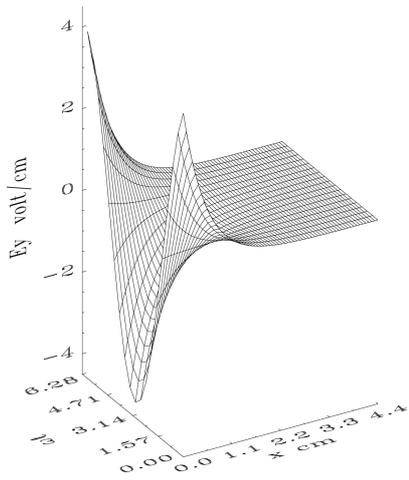


Fig. 1 Space-time profile of the transverse electric field E_y .

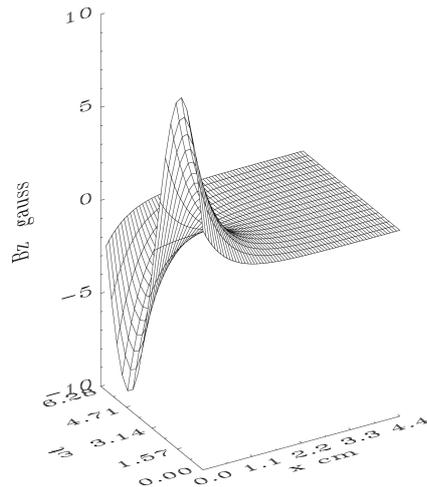


Fig. 2 Space-time profile of the wave magnetic field B_z

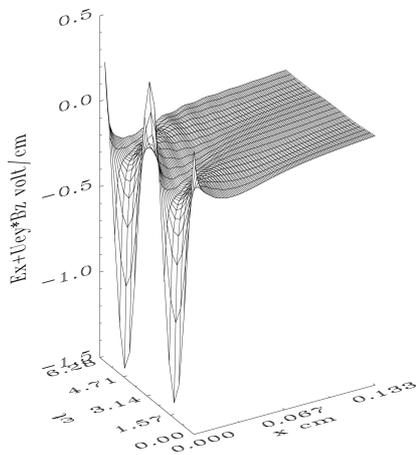


Fig. 3 Total acceleration term $E_x + u_{ye} B_z$ near the edge (up to 0.133 cm).

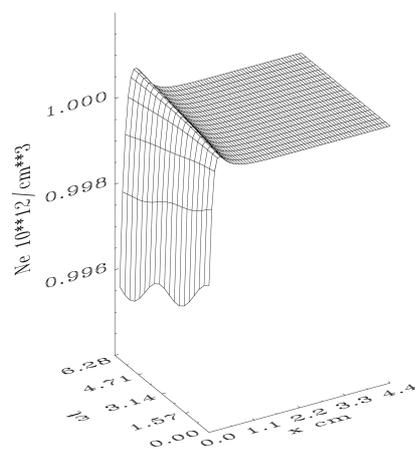


Fig. 4 Electron density

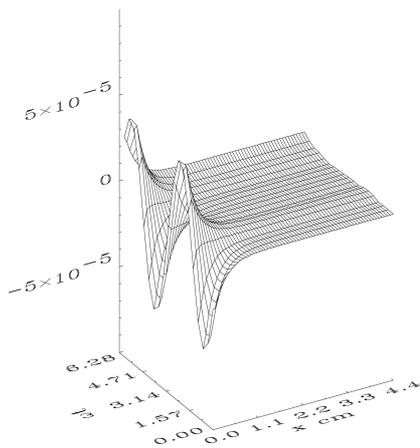


Fig. 5 Total current density $J_x = J_{ex} + J_{ix}$, in amp/cm² calculated at a frequency of 13.56 MHz..

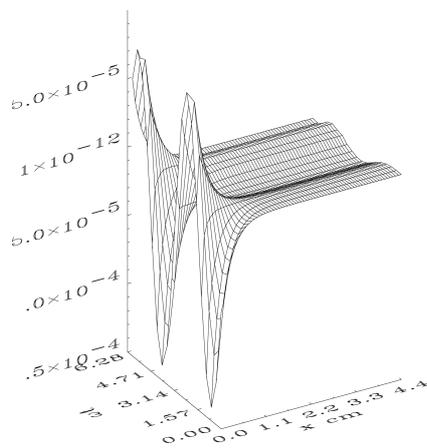


Fig. 6 Current density $J_x = J_{ex} + J_{ix}$ in amps/cm² calculated a frequency 6.78 MHz.